VIEWS OF THE INTERIOR OF THE MOON FROM A PROBABILISTIC GRAVITY INVERSION APPROACH.

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Introduction: The shape and location of density anomalies inside the Moon provide insights into processes that produced them and their subsequent evolution. Gravity measurements provide the most complete data set to infer these anomalies on the Moon [1]. However, gravity inversions suffer from inherent non-uniqueness. To circumvent this issue, it is often assumed that the Bouguer gravity anomalies are produced by the relief of the crust-mantle or other internal interface [2]. Using less restrictive assumptions, it was possible to infer a deep mass anomaly in the mantle underneath the central depression of the South Pole – Aitken basin [3] although the depth range of this anomaly could not be constrained. Deep three-dimensional density anomalies have not been generally studied in part because of the lack of methods to approach the non-uniqueness of gravity inversions.

In this work, we develop a method that provides a set of likely three-dimensional models consistent with the observed gravity data. In our approach, there is no need to constrain the depth of anomalies *a priori*. We invert the lunar gravity field and show the models of the interior compatible with observations.

Method: The volume of a sphere is divided in 6480 tesseroids and *n* Voronoi regions. Density is assigned to each Voronoi region, which can encompass one or more tesseroids. At each iteration, the algorithm can add or delete a region, or change its location [4, 5]. The optimal density of the each region is then obtained by linear inversion of the gravity field and the likelihood of the solution is calculated using Bayes' theorem. This likelihood is a function of how similar the observed gravity data is to that predicted by the model. The likelihood tends to increase with iteration and stabilizes at some point, following Metropolis-Hastings criteria. The algorithm then outputs an ensemble of models with good fit to the observed data and high posterior probability. The frequency with which features appear in this ensemble of models is proportional to their posterior probability. The ensemble might contain essentially similar interior density distribution models or many different ones, providing a view of the non-uniqueness of the inversion results.

Inversion of lunar gravity acceleration: We use the lunar radial gravity acceleration obtained by the GRAIL mission [6] up to spherical harmonic degree 400 as input data. The inversions were run for 10^6 steps using 100 parallel chains with different initial density models. After convergence was achieved, an ensemble of 10,000 density models was sampled from the posterior.

Fit to the input gravity acceleration data. Figure 1 shows that the gravity data used as input is similar to the mean gravity acceleration predicted by the models in the ensemble. This similarity indicates that, on average, models in the ensemble are consistent with the input data. The gravity field of the model ensemble is generally smoother than the original field. For example, it fails to recover the gravity signature of relatively small basins on the far side of the Moon and smooths over around Mare Nubium and Mare Humorum. We attribute this to the relatively coarse size of the tesseroids (10º x 10º) and their location.

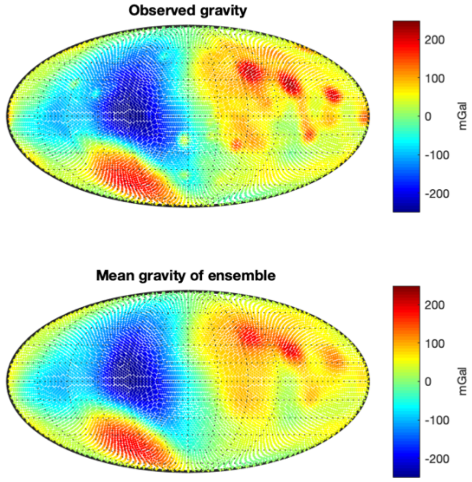

Figure 1 Input gravity acceleration data and mean gravity data of the group of output density models. Maps centered on 90°W, 0°N. The fit to the input data is very good which shows that the models in the ensemble are consistent with the data constraints, even though the gravity signature of smaller basins are not present in the gravity field of the ensemble.

Output lunar density models. The density models in the ensemble are sampled after convergence is achieved, and each fits the input gravity data well. This gives us confidence that the models provide an unbiased sample of the posterior probability distribution given the information contained in the gravity data. Because the constraints are the gravity data points and gravity inversions are non-unique, model features showing up with the same frequency in the ensemble should be taken as equally valid models of the interior.

Each view of the interior distribution of density in the Moon is shown by plotting the mean density of the tesseroids with color and the standard deviation of that value with the transparency. Tesseroids with a high density anomaly magnitude and low uncertainty are more visible than others with low anomaly or high uncertainty.

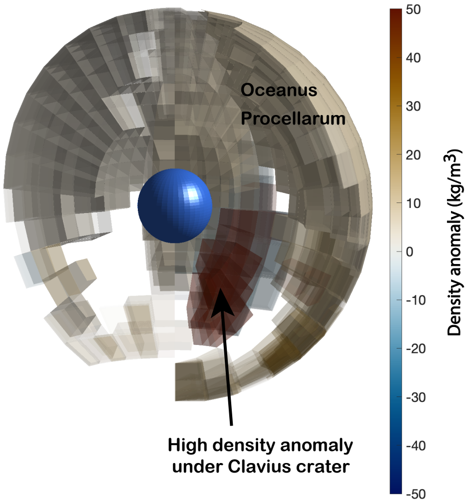

Figure 2 View of the interior of the Moon consistent with the gravity data. This density model shows a positive anomaly beneath the Clavius crater. The blue sphere represents the core of the Moon.

Figure 2 shows the mean density anomalies of a group of models that feature a deep positive density anomaly in the general area of the Clavius basin. The anomaly is centered at approximately 50°S and 10°E, at about 800 km depth. Density anomalies in this group of models remain relatively small and could be explained by mineralogical differences in the mantle. Major variations in crustal structure, such as the near side / far side dichotomy and the South Pole Aitken basin are also apparent, giving geological credence to this models.

Figure 3 shows a different view of the interior of the Moon obtained by a different group of models. This group of models points towards two high density regions with a much higher mass than in Figure 2. Explaining these mass anomalies would likely requires the involvement of core material or other exotic compositions. The most likely explanation for this difference is that the density anomaly of the crust was mapped into deeper locations making it necessary to have a very large mass to fit the input gravity data. Since this last view of the interior of the Moon is hard to reconcile with geologic information, it may be regarded as an unrealistic model.

Discussion: Our method embraces the non-uniqueness of gravity inversions and does not impose a single preferred view of the interior of the Moon. Instead, it seeks to provide all models consistent with the available gravity constraints. The models in Figure 2 show a deep positive anomaly in the Moon not previously identified but more work is needed to evaluate its robustness and understand its geodynamics significance. The model in Figure 3 is also consistent with the input gravity data but dynamically unrealistic given the very large magnitude of the anomalies. Prior information relating to the maximum density anomaly can be incorporated to correct for this problem. Geological knowledge and geodynamic analyses are important to evaluate the realism of each solution. In general, our gravity inversion approach can map out different models of the interior of the Moon or any celestial body that fits available gravity or other data.

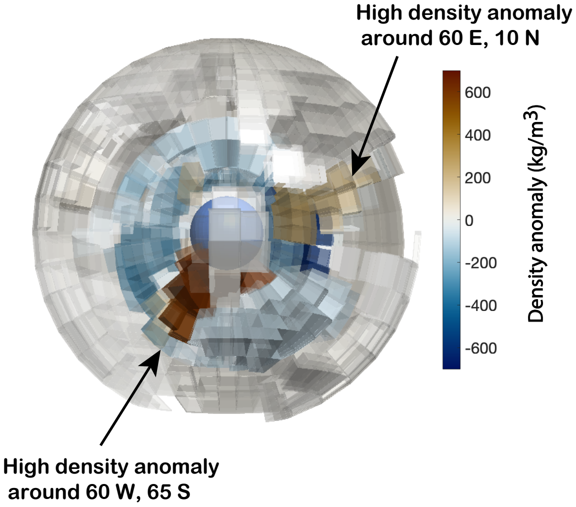

Figure 3 View of the interior of the Moon consistent with the data but not realistic with geodynamic information. This density model shows two very high density regions. The mass of these regions is probably too high for them to be stable over time. These mass anomalies probably correspond to density anomaly of the crust mapped into deeper locations.

References: [1] Wieczorek, M. A. (2006), *Treatise on Geophysics* 153-193. doi: 10.1016/B978-0-444-53802-4.00169-X. [2] Huang, Q., and Wieczorek, M. A. (2012) *J. Geophys. Res.,* 117 doi: 10.1029/2012JE004062. [3] James, P. B et al. (2019). *Geophys. Res. Lett.* 46, 5100-5106, doi: 10.1029/2019GL082252. [4] Izquierdo, K et al. (2019) *Geophys. J. Int.* 220, 1687-1699, doi: 10.1093/gji/ggz544, [5] Izquierdo, K. et al., (2019) *LPSC 50,* abstr. 2157. [6] Lemoine, F. G., et al. (2013), *J. Geophys. Res.* 118, 1676–1698 doi: 10.1002/jgre.20118.